Final Report for Period: 09/2009 - 08/2010 **Submitted on:** 06/14/2011

Principal Investigator: De Heer, Walter A. **Award ID:** 0605894

Organization: Georgia Tech Research Corp

Submitted By:

De Heer, Walter - Principal Investigator

Title:

Correlated Electron Effects in Small Clusters in Low Temperatures Molecular Beams

Project Participants

Senior Personnel

Name: De Heer, Walter

Worked for more than 160 Hours: Yes

Contribution to Project:

Post-doc

Graduate Student

Name: Liang, Anthony

Worked for more than 160 Hours: Yes

Contribution to Project:

Anthony is a gradate student who is fully supported by this project. He is working on the magnetic and ferroelectric properties of clusters.

Name: Bowland, John

Worked for more than 160 Hours: Yes

Contribution to Project:

John is a gradate student who is fully supported by this project. He is specializing in the the origin of electric dipole in ferroelectric clusters. He is also working on the magnetism of ferromagnetic clusters as well as on the Kondo effect.

Undergraduate Student

Technician, Programmer

Other Participant

Research Experience for Undergraduates

Organizational Partners

Other Collaborators or Contacts

We currently have ongoing collaborations with:
Professor Pieter Lievens (University of Leuven) on Kondo Clusters
and
Professor Andrei Kirilyuk (University of Neimegen) on Rare earth cluster magnetism

Activities and Findings

Research and Education Activities:

1. We have measured the ferroelectric properties of 9 ferroelectric niobium alloy cluster systems.
2.We measured the ionization potentials and the polarizabilities of these clusters.
3. We have verified the absence of electric dipole moments in sodium clusters. This is important since it contradicts theory and shows that inded the ferroelectric state in metal clusters is unusual.
4. We have found compelling evidence that the Cooper pairing is involved in the dipole moments.
5. We have been working on the Kondo effect in cobalt-silver and iron-silver clusters. We have preliminary evidence for the Kondo effect in clusters with more than 8 atoms. This work is still in progress.
6. We completed our investigations of the quantized ferromagnetic excited states in iron and cobalt clusters.
7. Efforts have begun to produce a resonant cavity to stimulate transitions in ferroelectric clusters in the beam.
8. In July 2007 Xiaoshan Xu finished his thesis and is now a post-doc with Janice Musfield.
9. In 2008 we have started a major effort to measure electric dipole moments in pure metal clusters and metal alloy clusters. We suspect that metallic clusters do not have dipole moments which will lead to a new definition of the metallic state in metal clusters.
10. Several designs for microwave cavities have been tested in order to find the optimum configuration for molecular beam spin resonance experiments. The system is expected to become operational in late 2008.
11. In 2008-2009 We have perfected electric deflection methods to measure the electric dipole moments and the polarizabilities of alkali clusters at low temperatures to very high precision.
12.We have initiated a collaboration with Andrei Kirilyuk (U. Neimegen) who spent May-June working in the lab on magnetic clusters. We hope to continue the collaboration and to measure clusters in the free electron laser in the Netherlands (FELIX)
13. We have finished the construction of the MBESR deflection magnets and we will be testing them in the coming year.

Findings:

Our major findings are:
1. Identification and characterization of the quantized ferromagnetic state in cobalt and iron clusters.
2. Completion of the studies of the ferroelectric properties of niobium and niobium alloy clusters.
3. Prilminary study of the Kondo effect in silver-iron and silver cobalt clusters.
4. Absence of dipole moments in sodium clusters.
5. High resolution polarizability measurements of sodium clusters with from 2 to 200 atoms.
6. Measurements of electric dipole moments in a variety of pure metal clusters and alloy clusters. It appears that metal clusters do not have dipole moments in contrast to theoretical predictions. This is an important finding that will be pursued in the coming year.
7. 2008-2009 We have pursued the electric dipole measurements of alkali clusters and verified the absence of dipole moments except for sodium 3 and sodium 6. These findings are at odds with molecular structure calculations.
8. We have initiated measurements of rare earth clusters (Tb Ho Gd, Dy TM) as well as several alloy clusters involving rare earth metals. We have found unusually large magnetic moments between N=20 and N=30. The magnetic properties of these metals are complex probably reflecting ferromagnetic to anti-ferromagnetic transitions. These are preliminary results and will require very careful study.
9. The electric dipole moments of rare earth metal clusters have also been measured. Some show rather large dipole moments but there does not appear to be a clear correlation with their magnetic properties.

11. We have published our results on the dipole moments of small sodium clusters in PRL

Training and Development:

Research in the cluster lab is multi-faceted and provides ample opportunity for students to acquire a very wide range of skills. These include:

1. ultra high vacuum skills
2. Laser skills (OPO, Excimer, Yag)
3. Data acquisition and data reduction.

The research experience fully equips the students for the challenges they will face in any future research position.

4. 1n July 2009 Anthony Liang has completed his thesis work and is currently writing his thesis (graduation date: Oct 27).
5. John Bowlan will finish his recent work on rare earth clusters and will start writing his thesis in December.
6. We trained Dutch graduate student Chris van Dijk during his visit in May-June 2009
7. Anthony Liang was graduated (PhD) in Dec. 2009 and started a post-doc at USC.
7. John Bowlan graduated in July 2010 and he currently a post-doc at the Fritz-Haber-Institut der MPG | Molecular Physics Dept.

Outreach Activities:

From July 2007 through July 2008 we have have 2 undergraduate students participate in our research efforts: Ryan Howard and Adam Anglyn.

Journal Publications

Yin, SY; Moro, R; Xu, XS; de Heer, WA, "Magnetic enhancement in cobalt-manganese alloy clusters", PHYSICAL REVIEW LETTERS, p. , vol. 98, (2007). Published, 10.1103/PhysRevLett.98.11340

Xu, XS; Yin, SY; Moro, R; Liang, A; Bowlan, J; de Heer, WA, "Nonclassical dipoles in cold niobium clusters", PHYSICAL REVIEW B, p. , vol. 75, (2007). Published, 10.1103/PhysRevB.75.08542

Xu, XS; Yin, SY; Moro, R; de Heer, WA, "Distribution of magnetization of a cold ferromagnetic cluster beam", PHYSICAL REVIEW B, p. , vol. 78, (2008). Published, 10.1103/PhysRevB.78.05443

Yin, SY; Xu, XS; Liang, A; Bowlan, J; Moro, R; de Heer, WA, "Electron pairing in ferroelectric niobium and niobium alloy clusters", JOURNAL OF SUPERCONDUCTIVITY AND NOVEL MAGNETISM, p. 265, vol. 21, (2008). Published, 10.1007/s10948-008-0332-

Bowlan, J; Liang, A; de Heer, WA, "How Metallic are Small Sodium Clusters?", PHYSICAL REVIEW LETTERS, p. , vol. 106, (2011). Published, 10.1103/PhysRevLett.106.04340

Books or Other One-time Publications

Web/Internet Site

Other Specific Products

Contributions

Contributions within Discipline:

The theme of our current work captures the essence of the entire metal cluster field. It examines the origin of metallic properties. We have demonstrated cryogenic phase transitions; the relation between ferromagnetism and superconductivity with their small particle counterparts; and most recently we are reexamining the most fundamental metal property of all: What makes a metal cluster metallic? The simplest answer is that it is a material that conducts electricity well. This is a property that arises because electrons in response to electric fields in the clusters. They move in such a way as to quench the electric fields. One consequence of this property, is that a metal particle cannot have an electric dipole moment, because it would cause electric fields inside it. One might expect that if a particle is very small, that this rule would break down, in fact several calculations have predicted electric dipole moments in clusters.

Our experiments indicate that even in the smallest sodium clusters, electric fields are quenched as they are in the bulk, that is --- the metallic phase will not tolerate voltage difference just like in the bulk. ---This suggests a new definition of the metallic state that extends from the smallest clusters to the bulk. It specifically diverges from the far more diffuse and conditional criteria used up to now, concerning density of states at the Fermi level.

This simple observation may leads to an astonishing conclusion. It provides a universal definition to define the metallic state and focuses on this extremely important and absolutely non trivial property of metals, as Nobel prize lauriate Robert Laughlin so astutely observed in his book: A Different Universe: ?The forces between electrons are enormous and their irrelevance is nothing short of astounding. Metallic behavior is an emergent organizational phenomenon. The electron sea makes sense because the metallic phase has formed.?

By the same token our research has bourn out another remarkable finding: clusters of superconducting metals like niobium in fact do have electric dipole moments! One would think that a superconductor is like a super metal, but actually this is not the case. In fact the electrons in superconductors are correlated, that is they act in unison over relatively large distances (not independently like in normal metals). In fact, the electrons in superconductors in a small superconducting particle behave more like a rigid object than like a fluid! Apparently this rigidity makes it possible for clusters of superconducting metals to have dipole moments.

While the observations of the dipole moments in superconducting clusters is well established, we are not yet sure if the explanation above is correct. If in fact is does turn out to be true, then this will be a major discovery in the field of superconductivity.

Contributions to Other Disciplines:

Note that the contribution to other disciplines is the same as the contribution within the cluster field. Cluster physics is about understanding the properties of bulk matter by examining the evolution of these properties as a function of their size. This is the beauty of the field.

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Contributions to Human Resource Development:

My cluster research group is very small: besides myself I have two graduate students. My main purpose is to transmit my enthusiasm for physics to them so that they can become independent Scientists.
My former graduate students and undergraduate students who have participated in this project have all found positions in science related fields.
Specifically:
former graduate students

Ramiro Moro: Professor of Physics at Cameron college.
Xiaoshan Xu, graduated in 2007 Currently post-doc with Janice Musfeldt
at UTK/ORNL, continuing his work on ferromagnetism. He is applying
for a postdoc position at Oakridge that is quite prestigious.
Shuangye Yin, graduated 2006 - now at UNC lab of Nikolay V. Dokholyan in theoretical biophysics.

Undergraduate students
Ryan Howard graduated '07 works at US patent office in D.C.
Adam Anglyn graduated '08 now in medical school

Contributions to Resources for Research and Education:

Our molecular beam methods, in particular the position sensitive detection method and the cryogenic laser vaporization source, have been copied in various laboratories. Currently, we are transferring this knowledge directly to other groups who are interested in learning the technique, like our colleagues in the University of Neimegen and the university of Leuven.

Contributions Beyond Science and Engineering:

Conference Proceedings

Categories for which nothing is reported:

Organizational Partners

Any Book

Any Web/Internet Site

Any Product

Contributions: To Any Beyond Science and Engineering

Any Conference